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(NASA-CR-130918) PLAGIOCLASE MINERALOGY
OF OLIVINE ALKALINE BASALT Final Report
(Texas Univ.) 69 p HC $5.50 CSCL 08G

N73-18368

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G3/13 17187

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TO: The National Aeronautics and Space Administration

FROM: The University of Texas at El Paso
Dr. Jerry M. Hoffer, Principal Investigator

SUBJECT: Final Report

Grant Number: NGR 44-012-147

Starting Date: June 1, 1970

Completion Date: October 15, 1972

Title: Plagioclase Mineralogy of Olivine Alkaline Basalt

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Date Jan. 10, 1973

I

FINAL REPORT

November, 1972

NASA GRANT NGR 44-012-147

Plagioclase Mineralogy of Olivine Alkaline Basalt

II

INTRODUCTION

The Potrillo Volcanics

The Potrillo volcanic field covers an area of approximately 400 square miles in southcentral New Mexico (Fig. 1). The volcanic rocks crop out on the La Mesa surface, i.e., La Mesa Basalts, and in the West Potrillo Mountains, i.e., West Potrillo Basalts. The Quaternary volcanics consist of cones and flows of alkali basalt.

Geographically, the Potrillo Volcanics can be divided into three regions: (1) the Santo Tomas-Black Mountain chain (La Mesa Basalt), (2) the Aden-Afton region (La Mesa Basalt), and (3) the West Potrillo Mountains (West Potrillo Basalt).

Purpose and Scope of the Investigation

The purpose of the study is three-fold. First, map the volcanic area and define the major volcanic stratigraphy. Second, investigate the relationships between composition and structural state of plagioclase feldspar in the alkali basalt. Third, determine of what use the above relationships could be employed to interpret thermal history and crystallization of earth and possibly lunar basalts.

The program includes both a geological and mineralogical study of the volcanic rocks. This investigation consisted first of field mapping to establish and identify the different rock types, volcanic features, to establish the geological history. Next samples were collected and

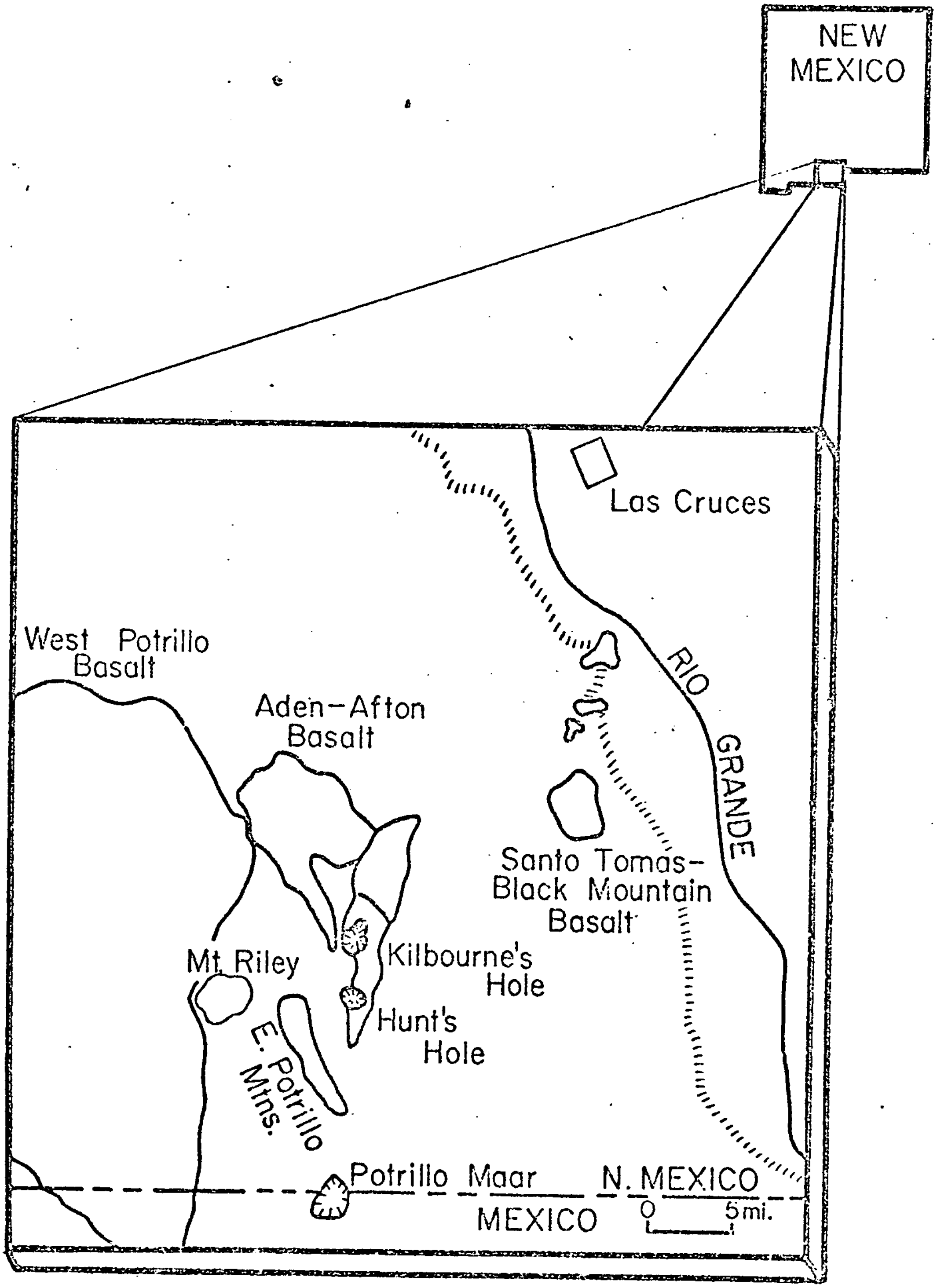

Fig. 1 Index map of the Potrillo Volcanic field

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analyzed petrographically to determine suitable rocks from the various stratigraphic units for study of plagioclase. Samples selected for further study were crushed and the plagioclase extracted for the determination of composition and structural state. These results were then related to the petrology and crystallization of the basalt.

METHODS OF INVESTIGATION

Field Mapping and Sample Collection

The summers of 1970, 1971, and June, 1972 were spent in field mapping of the Potrillo Volcanic field and collecting samples. Mapping was done on Army Map Service aerial photographs at scales of 1:55,500 and 1:18,500. Data were transferred to topographic and planimetric maps for construction of a final geologic map.

Samples were collected from representative units both laterally and vertically. The degree of vesicularity, weathering, jointing, and other physical characteristics were noted.

LABORATORY METHODS

Separation of Plagioclase

Before separation procedures were employed each collected sample was sliced and a thin section obtained. The thin section was examined to determine the amount of glass and size of the plagioclase. Samples were rejected that did not contain at least 20 percent plagioclase with an average groundmass width of 0.02 mm.

An outline of the separation procedure is given below (for details see Hoffer, 1966).

1. Crushing and screening of rock samples.
2. Preliminary separation with isodynamic separator.
3. Treatment with hydrochloric acid or oxalic-hydrochloric acid.
4. Final separation of groundmass and/or phenocryst plagioclase with isodynamic separator and heavy liquids.

Determination of Anorthite Content

The determination of An content of the plagioclase was by both chemical analysis and glass fusion. One gram of sample was needed for chemical analyses of K_2O, CaO, and NaO by X-ray fluorescence. If less than one gram was obtained through separation, the An content was determined only by glass fusion (see Hoffer, 1967b).

Duplicates were analyzed for most samples and if the results differed by more than 2 mole percent An the sample was rejected.

Determination of Percentage Glass and Size (the plagioclase crystals)

The amount of glass in each basalt sample was determined by point counting thin sections; 500 to 700 counts were made on each thin section. The positive identification of glass in many sections was difficult because of the presence of included magnetite and other opaque alteration products in and on the glass. Therefore, the estimates of glass content are probably no more accurate than ±10 percent.

The average width of the groundmass plagioclase was chosen as the parameter of size so that comparisons of texture could be made among the various samples; width was selected because of irregularities noted in the length of many crystals. The width was measured perpendicular to the albite twins on all crystals. The average crystal width was selected from at least 10 areas of the thin section by inspection and each measured with a micrometer ocular. The width of the average groundmass crystal in each sample represents the average of the 10 determinations. Duplicate determinations indicate an accuracy of approximately ±0.02 mm.

Determination of Structural State

Structural state determinations of the feldspar were made by X-ray diffraction methods utilizing the methods of Smith and Yoder (1956). The structural state of each plagioclase is reported in terms of the intermedicacy index, I.I. (Slemmons, 1962). This index is at present only a qualitative measure of the degree of disorder; the most ordered forms are assigned a value of 100 (I.I. = 100) and the most disordered forms 0 (I.I. = 0). Plagioclases intermediate between completely ordered and disordered forms are assigned values intermediate between 100 and 0. The intermediacy index is used here to denote a relative deviation from the boundary curves of "high" (I.I. = 0) and "low" (I.I. = 100) plagioclase; each interval not implying equal degrees of disorder.

Briefly, the X-ray diffraction procedure is as follows. A glass slide is smeared with "Vaseline" and 5 to 10 mg of powdered feldspar sprinkled on the slide. The slide is placed on the goniometer and scanned from 2θ 32° to 28°. The resulting reflections are indexed and the structural state determined utilizing the diagrams of Smith and Yoder (1956). If the angular position of the above reflections deviated by more than 0.02° (2θ) between the two patterns they were rejected and the sample rerun.

RESULTS OF INVESTIGATION

Geology of the Potrillo Volcanic Field

Introduction

The geology of the Potrillo field is summarized on the geologic map (see Plate I). For the purpose of discussion the geology of the three previously mentioned geographic sectors of the area will be presented separately.

Santo Tomas-Black Mountain Area

Introduction

Four eruptive centers, with volcanic products covering approximately 15 square miles, are located on the eastern margin of the La Mesa surface (Fig. 1). From north to south, the four centers are called Santo Tomas, San Miguel, Little Black Mountain, and Black Mountain. Black Mountain and Santo Tomas both display multiple eruptions, but the two intervening centers San Miguel and Little Black Mountain, display only a single extrusion of olivine basalt.

Petrography of the Lavas

The Santo Tomas-Black Mountain basalts are porphyritic and hypocrystalline. The amount of glass varies from approximately 50 percent in the quickly cooled, vesicular flow tops to less than 5 percent in flow interiors. Phenocrysts of plagioclase feldspar, olivine and pyroxene comprise from 15 to 30 percent of the rock. The fine-grained groundmass contains small plagioclase laths and small anhedral grains of pyroxene, averaging less than 0.1 mm in diameter, with minor amounts of magnetite, olivine, and light-to-dark interstitial glass.

Parallel to subparallel orientations of phenocrysts are common. Also abundant are glomeroporphyritic accumulations of olivine and areas of ophitic intergrowth of plagioclase and pyroxene.

Plagioclase feldspar is the most abundant mineral; it comprises from 22 to 48 percent of the total rock, occurring in both phenocryst and groundmass. The phenocryst platioclase is generally subhedral to euhedral with some crystals showing irregular outline due to resorption reaction. These crystals are moderately zoned with calcic cores (An_{60-65}) and more sodic exteriors (An_{55-60}). The groundmass plagioclase, averaging 0.05 mm, is unzoned and less calcic than the phenocrysts averaging An_{40} (andesine).

Pyroxene is present as phenocrysts, but more abundantly as groundmass. Phenocryst pyroxene is generally subhedral, averages 0.5 mm, and is typically moderate to dark brown in color with a moderate 2V (40 to 60 degrees). The color and 2V suggest titanium-rich augite. The groundmass pyroxenes, also dark brown, occur in small anhedral grains, averaging 0.05 mm in diameter.

Olivine is most abundant as subhedral to euhedral phenocrysts displaying locally strong glomeroporphyritic development. Its abundance, as phenocrysts, ranges from 17 to 62 percent. As a groundmass constituent olivine is sparse, occurring as small subhedral to anhedral grains. Many of the phenocryst olivines have irregular cracks and fractures with irregular edges; these boundaries are possibly due to resorption. A high 2V (80-85 degrees) and a negative sign indicate a high magnesium content, Fo_{80}-Fo_{65}.

Subhedral to anhedral magnetite, ranging in size from 0.08 to 0.05 mm, occurs as inclusions within olivine and pyroxene and as scattered subhedral crystals in the groundmass associated with the glass. The opaqueness of the glass is probably a function of the amount of included opaque oxides. Minor amounts of interstitial potassium feldspar and traces of feldspathoid (anaclime?) have been seen in the groundmass. The presence of the feldspathoid was verified by methyl blue staining.

Secondary calcite and opal fill vesicles near the top of the flows.

All samples examined appear to be essentially unaltered. In a few samples, especially near the top of the flows, evidence of minor alteration was noted. This consists of locally small brownish borders around some of the olivine phenocrysts (iddingsite?) and iron oxide stains from weathering.

The most distinctive characteristic of the individual Black Mountain-Santo Tomas flows is their phenocryst mineralogy. The mapping and identification of the individual flows were accomplished on the basis of normal field criteria at each center where it was discovered that certain flows contained unique phenocryst mineralogies.

The flows can be classified into three groups: (1) Type A — olivine-rich, (2) Type B — plagioclase-rich, and (3) Type C — both olivine and plagioclase (Hoffer, 1971).

Some flows, for instance flow 4 (BM-4) and flow 6 (BM-6) at Black Mountain, are very distinct and can be identified and traced easily in the field on the basis of phenocryst mineralogy. Other flows, although not as distinct megascopically, can be identified by determining the relative percentages of plagioclase, pyroxene, and olivine by point counting.

Volcanic Features

Black Mountain consists of eight volcanic cones (cinder and complex spatter types) and at least six major lava flows (Hoffer, 1969). The Black Mountain cinder cone, located in the center of the area, is almost symmetrical in outline with a diameter of about 2,000 feet and a height of over 300 feet. Six lava flows, ranging in thickness from 5 to 10 feet, surround the cinder cone; only the youngest flow can be traced to a specific cone, Black Mountain, where it appears to have been extruded from a lateral vent.

At Little Black Mountain and San Miguel only a single flow of olivine basalt is present. Both flows appear to have been extruded from small cones located at the west end of the flows.

The Santo Tomas region contains a major cinder cone and three associated flows. The flows, ranging in thickness from 7 to 18 feet, were extruded from the southwest, most probably from the Santo Tomas cone, and flowed northeastward from the La Mesa surface into the Rio Grande Valley.

Sequence of Flows

On the basis of topographic position and other field relationships, the sequence of extrusion has been established at Black Mountain and Santo Tomas (Hoffer, 1969). Once the sequence was determined at these multiple centers correlations were sought for the entire extrusive sequence among the four centers. The unique phenocryst mineralogies of the individual flows suggest a method of correlation represented by seven periods of basaltic extrusion among the four centers (Hoffer, 1971).

The K-Ar dates indicate the flows are younger than 0.3 m.y. (Denison, personnel communication, 1970, ~~Fig. 2)~~. Because these young age dates overlap they do not support or reject the proposed sequence of extrusion.

Aden-Afton Area — Aden Basalt

Introduction

The Aden Basalt is defined as the lavas that crop out in Aden cone and the adjacent areas north, east, and southeast of the crater (Kottlowski, 1953). The Aden area covers approximately 30 square miles and consists of thin vesicular flows with associated shield, spatter, and explosion-collapse craters and depressions. On the basis of petrography and field relationships the Aden Basalts can be divided into two members, an older series of flows termed member 1 and a younger unit, member 2.

Petrography of the Lavas

The lavas of the Aden Basalt are hypocrystalline and microporphyritic with subhedral to euhedral microphenocrysts of plagioclase, olivine, and pyroxene set in a fine-grained groundmass of subhedral plagioclase, euhedral pyroxene, feldspathoid, and glass. The microphenocrysts, averaging less than 15 percent, are less than 1 mm in diameter and are commonly golmeroporphyritic. The groundmass is subophitic to intersertal with lath-shaped plagioclase crystals in parallel to subparallel fabric with interstitial grains of pyroxene and patches of glass.

Plagioclase feldspar occurs as microphenocrysts of labradorite whereas that in the groundmass is more sodic ranging from calcic andesine to sodic labradorite (An_{45} to An_{55}). Phenocryst plagioclase shows pronounced normal and reverse zoning whereas the groundmass plagioclase is unzoned.

Olivine occurs as subhedral to euhedral microphenocrysts and comprises over one-half of the total phenocrysts. Minor amounts of olivine occur as small anhedral groundmass crystals.

Older flows of the Aden Basalt (A_1) contain more olivine and less pyroxene than the younger (A_2) flows (Table 1). Preliminary studies indicate a significantly higher pyroxene/olivine ratio for the A_2 flows.

Pyroxene is sparse as microphenocrysts but abundant in the groundmass. It is subhedral to anhedral, moderate to dark brown, and has a moderate 2V (i.e., less than 50 degrees).

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	ADEN BASALT		AFTON BASALT		
	Member 1 (A_1) Percent	Member 2 (A_2) Percent	Member 1 (Af_1) Percent	Member 2 (Af_2) Percent	Member 3 (Af_3) Percent
Plagioclase	22.2	23.2	23.4	16.1	15.5
Olivine	16.7	11.5	15.1	13.1	11.5
Pyroxene	37.5	41.9	33.8	46.0	48.5
Glass	13.7	13.2	18.5	14.5	12.5
Opaques	9.9	10.2	9.2	10.3	12.0
	100.0	100.0	100.0	100.0	100.0

TABLE 1

Modal mineralogy of the Aden-Afton Basalts (A_1 = oldest Aden flow A_2 = youngest Aden flow, Af_1 = oldest Afton flow, Af_2 = middle Afton flow, Af_3 = youngest Afton flow).

Subhedral to anhedral magnetite-ilmenite, ranging in size from 0.1 to 0.05 mm occurs as inclusion within olivine and pyroxene and as scattered subhedral crystals and needles in glass. Minor amounts of feldspathoid are present in the groundmass.

All samples appear to be essentially unaltered; minor alterations consist of narrow brownish rims (iddingsite) around some of the olivine crystals and iron oxide stains from weathering of opaques. Minor calcite and opal occur as vesicle fillings. A complete listing of the modal mineralogy of the Aden Basalt, and the Afton Basalt, are given in Table 1.

Flow Sequence

At least two major periods of extrusion can be identified within the Aden Basalt field. The first period is represented by lavas located north and east of Aden Cone at the lower topographic levels. Lying above the older A_1 flows are younger flows designated A_2. The A_2 flows are associated with north-south lineaments (collapse pits and troughs) or as isolated outliers (Plate 1).

The Aden flows are younger than the Afton flows because where the two formations are in contact the Aden flows appear to onlap the Afton Basalt. In addition, a heavier cover of alluvial sand on the Afton lavas indicates an older age.

Volcanic Forms

Volcanic forms in the Aden Basalt field consist of both craters and depressions. The crater types include a small shield cone, Aden Cone, which is one of the most prominent features in the area, and several spatter and explosion-collapse craters (Plate 1).

The spatter cones are small and occur on the flanks and interior of Aden Cone. Several explosion-collapse craters occur approximately 1 mile southeast of the Aden Cone. These craters consist of a rim, 10 to 30 feet high, of large angular fragments of dense basalt which enclose an interior portion of thin lava flows. The flows are nearly horizontal in the interior of the craters, but dip quite steeply toward the interior near the blocky rim, indicating central collapse after construction of a fragmental rim.

Depressions are abundant features in the Aden Basalt field. There are two kinds: Collapse pits of circular plan and elongate or linear collapse troughs. The collapse pits occur most abundantly in the younger flows (A_2). They range in depth from 15 to 55 feet, in diameter from 100 to 500 feet, and interior slopes range from 15 to 90 degrees. In the depressions with steepest interior slopes (greater than 45°) the walls are composed of concentric fractured slump blocks with the fracture planes dipping at high angles toward the outside of the depression.

The collapse troughs occur in two major areas within the Aden Basalt (Plate 1). These zones, although not entirely continuous, extend for several miles with a north trend. The western depression area (approximately 2-1/2 miles southeast of Aden Cone in T26S, R2W) can be traced for a distance of several miles. The eastern depression zone, although not as distinct, occurs approximately 4 miles east of Aden Cone (in T25S, R2W, and T26S, R2W). The linear depressions are generally symmetrical in cross section and range in depth from 15 to 38 feet.

The origin of these depressions is not known; some may represent collapsed lava tubes. However, several of the troughs appear parallel to regional structural trends which can be traced north and south into the Quaternary sediments where these lineaments are expressed as faults. They may be fissure zones through which the Aden lavas were emplaced and later collapsed as lava withdrew down the vent(s). Circular collapse pits also occur along these linear trends.

Aden-Afton Area — Afton Basalt

Introduction

The Afton Basalt is defined as the lavas that crop out south and southeast of Afton (T26S, R1W); the Afton flows are spacially distinct from the Aden Basalt flows. Three periods of basalt extrusion can be identified. Kottlowski (1960) designated two basalt formations, Qb_1 and Qb_2, but detailed mapping indicates that three, not two, periods of basalt extrusion occurred from related vents. Therefore, three basalt members make up the Afton Basalt. A comparison of the flow designations of Kottlowski and this author is given in Table 2.

Petrography of the Lavas

The basalt flows of the Afton Basalt are hypocrystalline, microporphyritic, and vesicular. Microphenocrysts average approximately 15 percent and are composed of olivine and minor plagioclase. Intergranular to intersertal textures show a pattern of small plagioclase laths, interstitial granules of pyroxene, irregular patches of glass, and minor feldspathoid.

Kottlowski (1953)	Hoffer (1972)
Qb_3 (Aden Basalt)	Aden Basalt
	Member 2 - A_2
	Member 1 - A_1
	Afton Basalt
	Member 3 - Af_3
Qb_2	Member 2 - Af_2
Qb_1	Member 1 - Af_1

TABLE 2

Units of Aden-Afton Basalt Field

Labradorite (An_{50} to An_{65}) occurs as sparse subhedral to euhedral phenocrysts. These phenocrysts show both normal and reverse zoning. The more abundant groundmass plagioclase average 0.98 mm and shows trachytic texture.

Olivine occurs almost exclusively as phenocrysts in glomeroporphyritic masses, its composition is magnesium-rich as indicated by a high 2V and negative sign.

Clinopyroxene, the most abundant mineral, occurs in small granules or as short tabular crystals; it ranges from light-brown to a deep reddish-brown. Microphenocrysts have a low 2V, less than 40°, and are probably pigeonite.

Glass, which ranges from less than 5 percent to over 30 percent of the rock, occurs as irregular patches and masses in the groundmass. The glass is light to dark-brown; its opacity is a function of the amount of included iron oxides.

Minor alteration products consist of thin rims of iddingsite around olivine crystals and staining by iron oxide. Secondary minerals, which occur as vesicle fillings, consist predominantly of clay and calcite.

Flows of both the Aden and Afton formations are similar mineralogically, and both show an increase in pyroxene and a decrease in olivine and plagioclase upward in the section suggesting differentiation of the magma (see Table 1).

Volcanic Forms

Craters and depressions occur in the Afton Basalt field. A cluster of four cinder-spatter cones, the Gardner Cones, is located approximately

4 miles south of Afton; a small spatter cone occurs just north of Hunts Hole (Plate 1).

The most spectacular craters are the maar volcanoes of Kilbourne and Hunts Holes. The craters range from 1 to 3 miles in diameter, are roughly circular, and are surrounded by a raised rim (DeHon, 1965b). Stratigraphically the craters include four major units: (1) basal flat-lying beds of the Santa Fe Formation, (2) olivine basalt flow, (3) bedded tuffs of both air fall and base surge origin and (4) an upper unit of Recent alluvium.

DeHon (1965b) attributes the origin of the maar craters to phreatic explosions caused by the conversion of groundwater to steam by an intruding magma.

One major collapse trough occurs in the Afton Basalt; it is located approximately 1 mile north-northeast of the Gardner Cones (Plate 1). Alignment of the eastern trough and pits might suggest a north-south fault connected with Kilbourne and Hunts Holes. However, an alignment also exists with the craters and a depression trough within the Afton Basalt.

Flow Sequence

Three periods of extrusion can be identified within the Afton Basalt. The oldest member is designated Af_1; this flow is exposed in the walls of Kilbourne and Hunts Holes. It is covered to the north beneath alluvial sand and a younger flow, Af_2. The Af_2 lava is associated with a major collapse trough (Plate 1). The youngest flows are designated Af_3; they consist of three to four local flows covering 1/4 square mile near the Gardner Cones. These flows represent small central eruptions which crop out on the east and south flanks of the cones.

West Potrillo Mountains

Introduction

The West Potrillo Mountains, covering over 300 square miles, consist of a broad topographic high constructed of coalescing lava flows on the western edge of the La Mesa surface. The plateau rises 400 to 800 feet above the La Mesa (4,200 feet) and is dotted by numerous volcanoes that reach elevations of nearly 5,500 feet.

Petrography of the Lavas

Two contrasting mineralogies make up the lavas of the West Potrillos. The older type, member 1, is of predominantly plagioclase with minor olivine and pyroxene whereas the younger basalt, member 2, is richer in olivine and pyroxene and poorer in plagioclase (Table 3).

The member 1 lavas, PB_1, are porphyritic to nonporphyritic, holocrystalline to hypocrystalline, subophitic; phenocrysts are composed predominantly of plagioclase feldspar. The fine- to medium-grained groundmass, 0.07 to 0.15 mm, is composed of mainly subhedral laths of plagioclase and lesser amounts of pyroxene, olivine (and iddingsite), opaques, and glass.

Plagioclase, averaging over 50 percent, is sodic labradorite in the groundmass and labradorite as phenocrysts.

	PB_1	PB_2
Olivine	7.2	16.9
Iddingsite	6.9	Tr
Plagioclase	51.9	21.1
Pyroxene	9.0	39.4
Opaques	15.4	11.8
Glass	9.6	10.8
	100.0%	100.0%

TABLE 3.

Modal mineralogy of the West Potrillo Basalts (PB_1 - oldest member and PB_2 youngest member).

Olivine occurs predominantly in the groundmass, but occasionally as phenocrysts highly altered to iddingsite; the groundmass crystals show less alteration.

Pyroxene is present as small granules or as elongate fibers or needles associated with opaques and glass. The moderate to dark brown color of the pyroxene suggests titanium-rich augite.

The member 2 lavas, PB_2, are micorporphyritic, hypocrystalline, and subophitic to hyaloophitic. Microphenocrysts are predominantly olivine, with minor plagioclase and pyroxene. The fine-grained groundmass, 0.01 to 0.07 mm, is mostly pyroxene with lesser amounts of plagioclase, opaques, and glass with minor olivine.

Pyroxene, averaging approximately 40 percent, occurs as light to dark brown subhedral to anhedral crystals. Most of the larger crystals are zoned.

Olivine is generally unaltered and displays subhedral to euhedral outline. A high 2V and a negative sign indicate a high magnesium content.

Plagioclase, almost all of which occurs in the groundmass, is calcic labradorite (An_{60}-An_{70}). It is present as subhedral laths in parallel to subparallel orientation.

Opaques are scattered throughout the groundmass as anhedral crystals and masses associated with the glass.

Volcanic Features

The most prominent features of the West Potrillo Mountains are cinder cones; over 130 cones occur in the range. In addition, two maar craters, Mount Riley Maar and Malpais Maar, occur in the field.

The cinder volcanoes occur as both individuals and in cone complexes. The individual cones range from 200 to 500 feet in height and are 1,000 to 3,000 feet in diameter. They consist predominantly of cinder with a spatter rim. Most are of horseshoe shape in plain view with the breached rim exposing an emergent lava flow. The cinder-spatter cone complexes are generally composed of three to six individual cones arranged in linear pattern. These complexes extend up to 1-1/2 miles in length with a north-south trend. The cone complexes are more highly eroded than the individual cinder cones.

Two maar volcanoes have been identified in the West Potrillo Mountains. These explosive craters are designated Mount Riley Maar and Malpais Maar; they are located 5 miles west of Mount Riley and 3 miles east of Malpais, respectively (Plate 1).

The Mount Riley Maar is nearly circular in outline with an interior diameter of approximately 2,500 feet. The raised rim is composed of thin parallel layers dipping 5 to 30 degrees away from the crater interior. The deposits are composed of poorly sorted, subangular to subrounded basalt, scoria, mineral, and lithic fragments. Mineral fragments include large crystals of feldspar and olivine-enstatite aggregates up to 3 inches in size. Similar olivine-enstatite masses occur as bomb-cores and inclusions at Kilbourne Hole and Potrillo Maar, respectively (Carter, 1970). Large fragments of dense basalt up to 6 feet in diameter have been found in the rim deposits. The east and northeast floor of the crater is covered by a thin basalt flow that appears to have emerged from a vent within the crater.

In Malpais Maar the rim tuffs outline a broad area 800 feet long and 600 feet wide. The rim volcanics are composed of silt- to sand-sized particles displaying gentle undulating bed forms and dipping cross-bedded layers. These base surge deposits contain fine-grained thin, parallel layers and blocks of air fall origin. The air fall blocks have produced bedding sag structures in the underlying tuffs.

Within the maar occur two individual cinder-spatter cones and a large cinder-spatter cone complex with two or three associated vents. Two flows have extruded from this complex and covered the southern and eastern floor of the maar, breached the rim, and flowed out of the crater.

Flow Sequence

Two major periods of extrusion can be identified within the West Potrillo Mountains. The first period is represented by lavas northwest and west of Aden Cone, PB_1 (Plate 1). The basaltic flows crop out in a series of fault blocks, striking northwest, and overlie acidic to intermediate tuffs, flows, and breccias of Tertiary age.

The PB_2 flows onlap the PB_1 lavas just west of Aden Cone and are therefore younger. These flows make up the bulk of the range and are overlain by cinder cone deposits and associated local flows.

Xenoliths

In addition to the occurrence of primary plagioclase feldspar, exotic magacrysts of anorthoclase, lime-anorthoclase, potash andesine, and plagioclase occur in the Potrillo Basalts. The feldspar xenoliths occur loose crystals on the flanks of cinder and maar cones, in the cores of ejected bombs, and in lava flows. Associated with the feldspar crystals are nodules and crystals of olivine-spiner pyroxene, and amphible. These xenoliths are associated primarily with the younger, PB_2, basalts.

CHEMISTRY OF THE BASALTS

Nine complete chemical analyses of the Potrillo Basalts have been determined; three from the Aden-Afton field and six from the West Potrillo Mountains. The chemical oxides are given in Table 4.

The Potrillo Basalts are classified as alkaline olivine basalts based on the ratio of total alkali to silica (Kuno, 1968). The analyses show low to moderate silica, moderate Al_2O_3, high alkalis, and moderately high TiO_2. The analyses compare favorably with normal alkali basalt, but are somewhat higher in total alkalis, especially K_2O (Nockolds, 1954).

The lavas of the West Potrillo Mountains show two distinct chemistries. The WP_2 basalts are lower in SiO_2 and higher in M_9O, Na_2O, CaO and TiO_2 than the WP_1 basalts; these differences are reflected in the modal mineralogies of lavas (see Table 3).

The basalts of the Aden-Afton region are very similar chemically to the younger lavas of the West Potrillos (WP_2). However, the Aden-Afton basalts are noticeably lower in Na_2O and TiO_2.

One significant difference between the three groups of lavas is their TiO_2 content. The TiO_2 values of the Aden-Afton flows average 2.28 percent, those of the WP_2 flows 2.40 percent, and 2.09 percent for the WP_1 lavas. These relative differences in TiO_2 content correlate with results reported by Renault (1970). Differences in the TiO_2 content could be due to differentiation (Kuno, 1968) or structural setting (Renault, 1970).

	Af_1-1	Af_2-1	A_2-1	WP_2-1	WP_2-2	WP_2-3	WP_1-1	WP_1-2	WP_1-3
SiO_2	44.89	43.91	45.03	44.63	44.37	44.21	50.50	49.49	49.49
TiO_2	2.12	2.37	2.37	2.60	2.37	2.21	2.08	2.16	2.03
Al_2O_3	14.81	15.64	15.67	15.92	15.89	15.01	16.00	15.92	16.05
Fe_2O_3	3.55	2.47	1.86	3.66	4.13	4.82	4.46	6.12	6.40
FeO	7.98	8.42	9.22	6.56	6.82	6.07	6.75	5.94	5.67
MnO	0.18	0.17	0.17	0.14	0.16	0.14	0.15	0.14	0.15
MgO	10.58	9.37	9.74	9.17	7.30	10.34	4.37	5.13	4.81
CaO	10.74	11.43	10.08	10.36	10.09	10.94	8.27	7.97	8.12
Na_2O	2.56	2.86	3.29	4.70	4.48	3.67	3.69	3.44	3.64
K_2O	1.35	1.63	1.85	0.90	2.27	1.65	1.76	1.64	1.59
H_2O	0.97	0.92	0.52	1.06	1.90	1.11	1.66	1.08	1.31
P_2O_5	0.43	0.52	0.51	0.64	0.74	0.48	0.62	0.67	0.64
	100.16	99.78	100.31	100.17	99.71	100.65	100.49	100.26	100.13

TABLE 4

Chemical oxides of the Potrillo Basalts (Af_1-oldest Afton member, Af_2-intermediate Afton member, A_2-youngest Aden member, WP_2-youngest West Potrillo member, and WP_1-oldest West Potrillo member. Analyst-Tadashi Asari, Japan Analytical Chemistry Research Institute).

RESULTS OF LABORATORY STUDIES

Introduction

Variations in composition (mole percent An and Or content), structural state of plagioclase, and texture (size of groundmass plagioclase and amount of associated glass) have been found in samples of the West Potrillo and Aden-Afton Basalts. These results are presented along with a discussion of the relationships of each in detail below.

Variations of Texture

General

All samples collected are microporphyritic to nonporphyritic and hypocrystalline in texture. The investigation of texture, in this case the determination of the average width of the groundmass plagioclase and the amount of associated glass, was made in order to obtain a qualitative index for the rate of cooling of each sample. This was attempted to determine the relationship of the rate of cooling to An and Or content and/or structural state of the plagioclase.

The groundmass plagioclase crystals range in width from 0.168 mm in the coarse-grained rocks to approximately 0.01 mm in the finer-grained samples.

In every thin section examined glass was found in association with plagioclase groundmass. The percentage of glass ranges from 3 to 43 percent.

Relationship of Glass Percentage and Size of Groundmass Plagioclase

The relationship of the proportion of glass to average size of the groundmass plagioclase in all samples is given in Figs. 2 and 3. The results indicate that samples containing the most glass are those possessing the smallest size plagioclase groundmass crystals. The correlation coefficient, $R = -0.72$, indicates a marked correlation. This same relationship has been verified in tholeiite basalt (Hoffer, 1966c). A much higher correlation ($R = -0.84$ and -0.87) between size of groundmass plagioclase and glass content is evident in samples from two individual flows (see Fig. 3).

Variations of Composition of the Plagioclase

Variations in the mole percent An and Or content of both groundmass and phenocryst plagioclase have been found in the basalts. The An and Or content of the plagioclases are summarized in Figs. 4 and 5.

The An content of the groundmass plagioclase samples ranges from An_{49} to An_{70}; the average content is $An_{59.5}$ (Fig. 4). The plagioclase phenocrysts range in composition from An_{53} to An_{73} with an average of $An_{62.2}$ (Fig. 4).

Mole percent Or in groundmass plagioclase ranges from 2.5 to 7.4, averaging $Or_{4.2}$ (Fig. 5). The phenocryst plagioclase are poorer in mole percent Or ranging from 2.2 to 4.7 and averaging $Or_{3.3}$.

Composition Versus Size of Groundmass Plagioclase

A moderate negative correlation (linear) was found to exist between An content and size of the groundmass plagioclase ($R = -0.51$) as shown in Fig. 6. This means that as the size of the groundmass plagioclase increases the An content decreases.

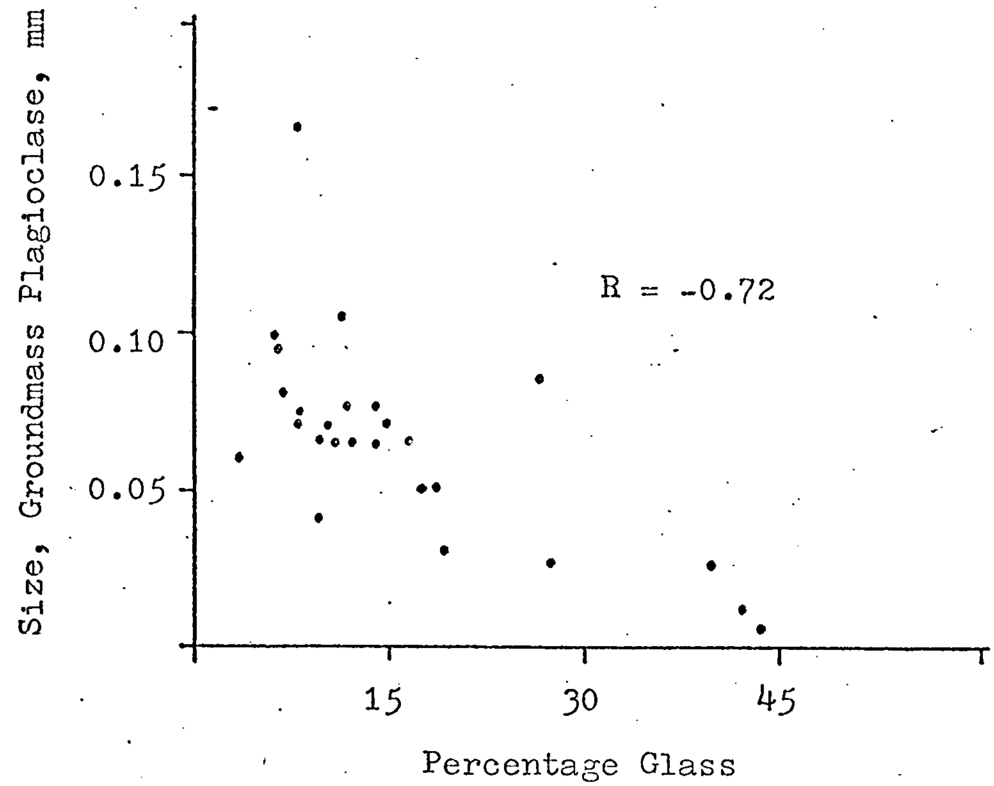

Fig. 2. Glass percentage versus size of groundmass plagioclase (R = linear correlation coefficient)

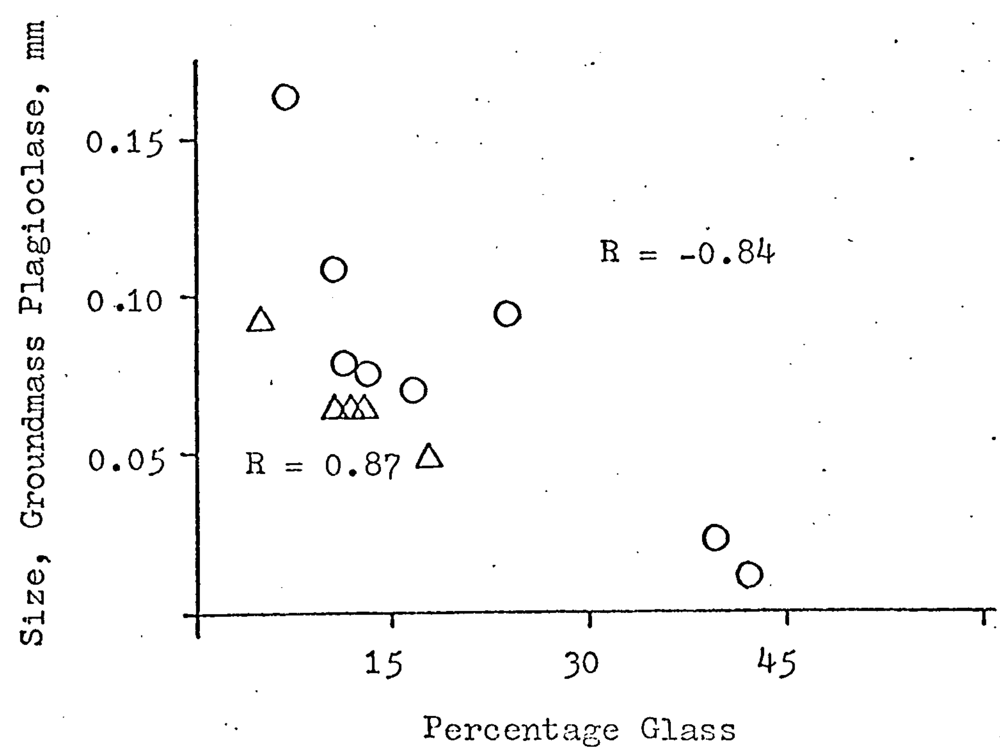

Fig. 3. Glass percentage versus size of groundmass plagioclase from two flows (R = linear correlation coefficient)

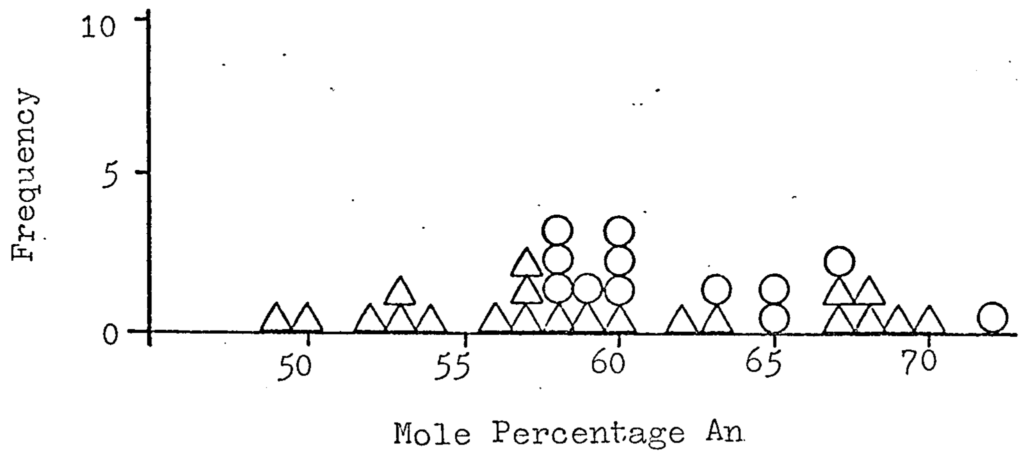

Fig. 4. An content versus frequency (circles = phenocrysts and squares = groundmass)

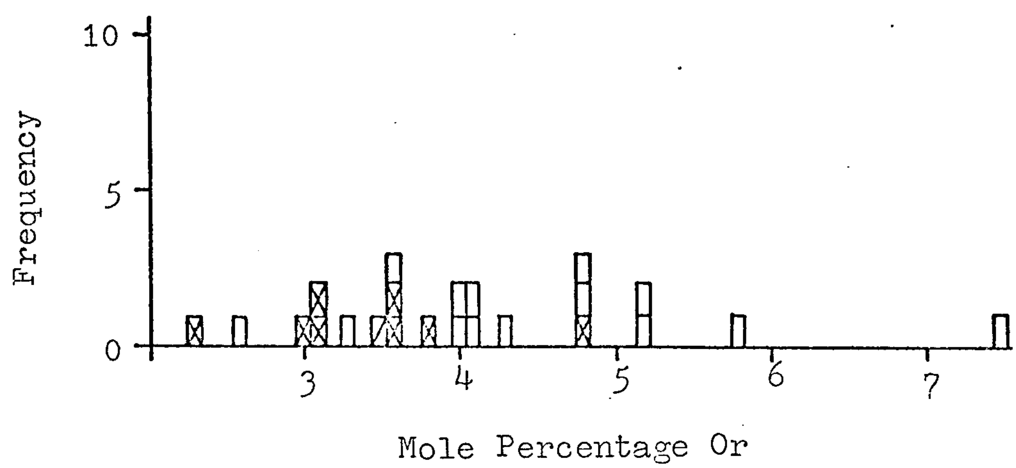

Fig. 5. Or content versus frequency (open rectangles = groundmass and crossed rectangles = phenocrysts)

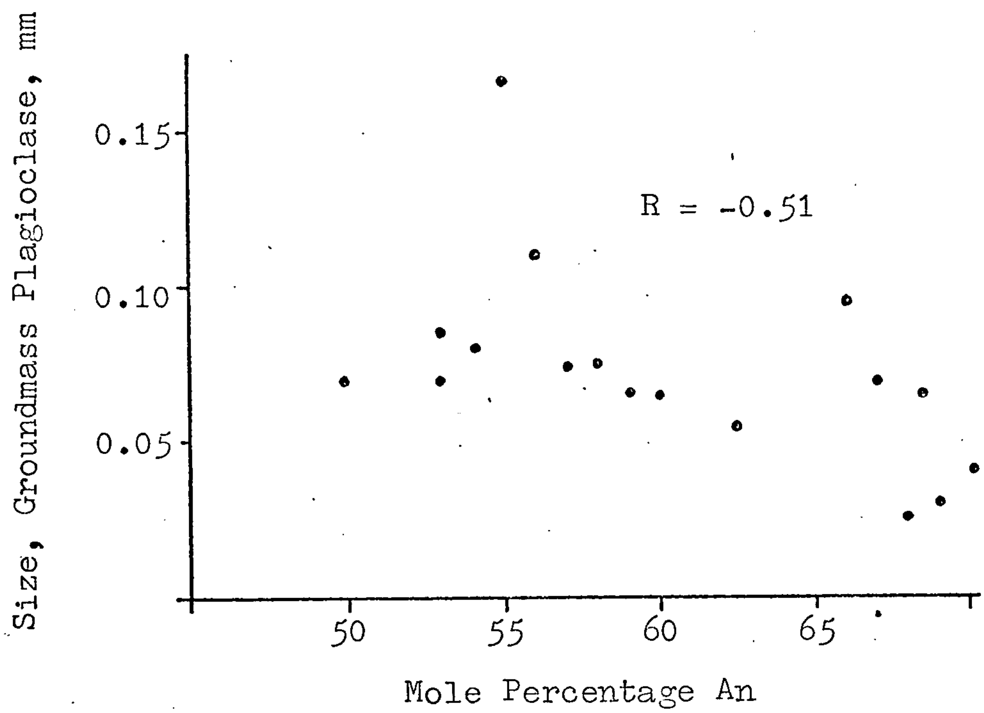

Fig. 6. Composition versus size of groundmass plagioclase

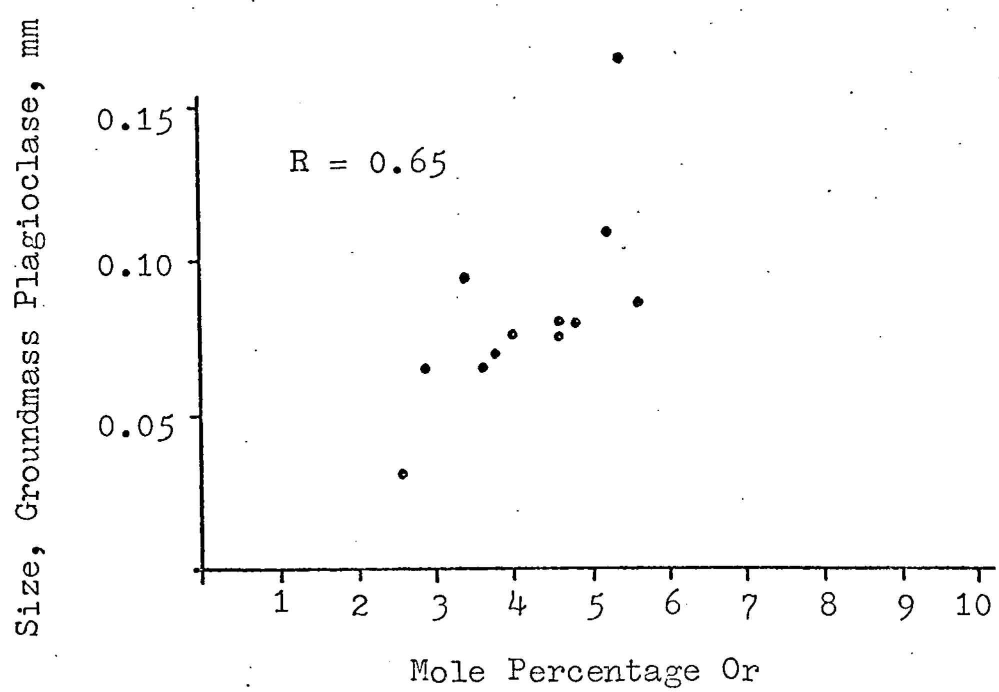

Fig. 7. Composition versus size of groundmass plagioclase

A higher moderate positive correlation (linear) was found to exist between Or content and size of the groundmass plagioclase (R = 0.65) (Fig. 7). Plagioclases of largest size possess the highest Or contents and those of smallest size the least.

Composition Versus Amount of Associated Glass

The variation of An content of the groundmass plagioclase with the proportion of associated glass was found to display a moderate positive correlation (linear), as shown in Fig. 8. On the other hand, a much weaker negative correlation (linear) is seen between mole percent Or and associated glass content (R = - 0.48) (Fig. 9).

In summary, moderate correlations exist amount An and Or content and crystal size and between Or and An content and proportion of associated glass.

Variations of Structural State of the Plagioclase

General

Variations were found in the structural state (degree of disorder) of both the phenocryst and groundmass plagioclase. The structural state of the plagioclase ranges from low (ordered) to high (disordered) as is shown in Plates 2 and 3.

Structural State of Groundmass Plagioclase

The structural state of the groundmass plagioclase in the Potrillo basalts varies from high-intermediate to high. Expressed as the intermediacy index, I.I., the values range from -10 to 55 (negative values

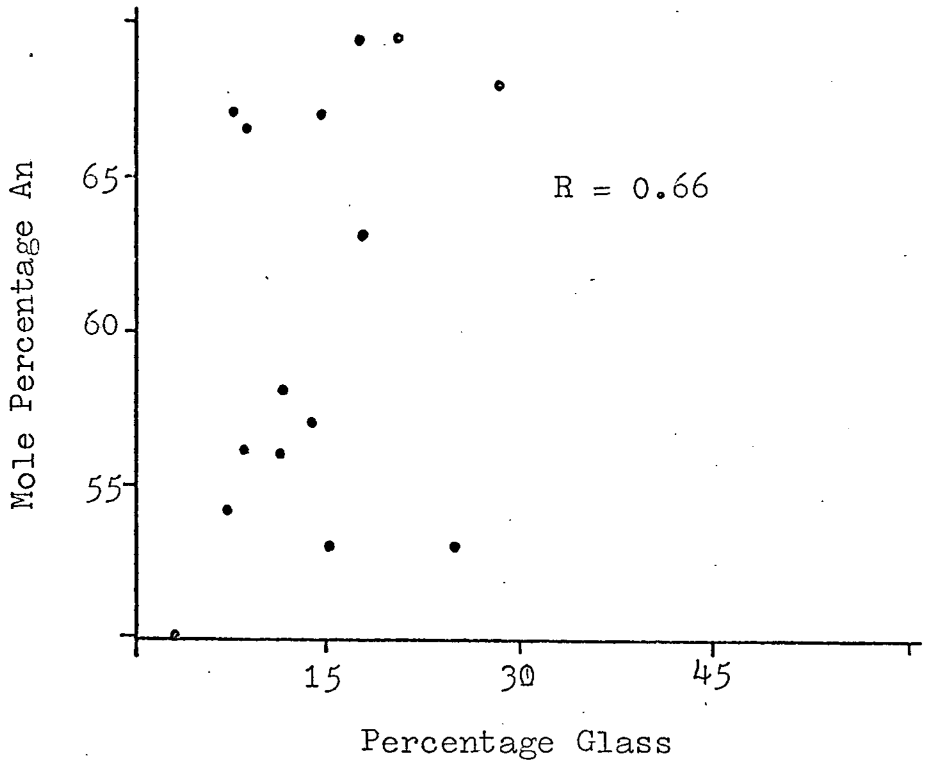

Fig. 8. An content versus percentage glass

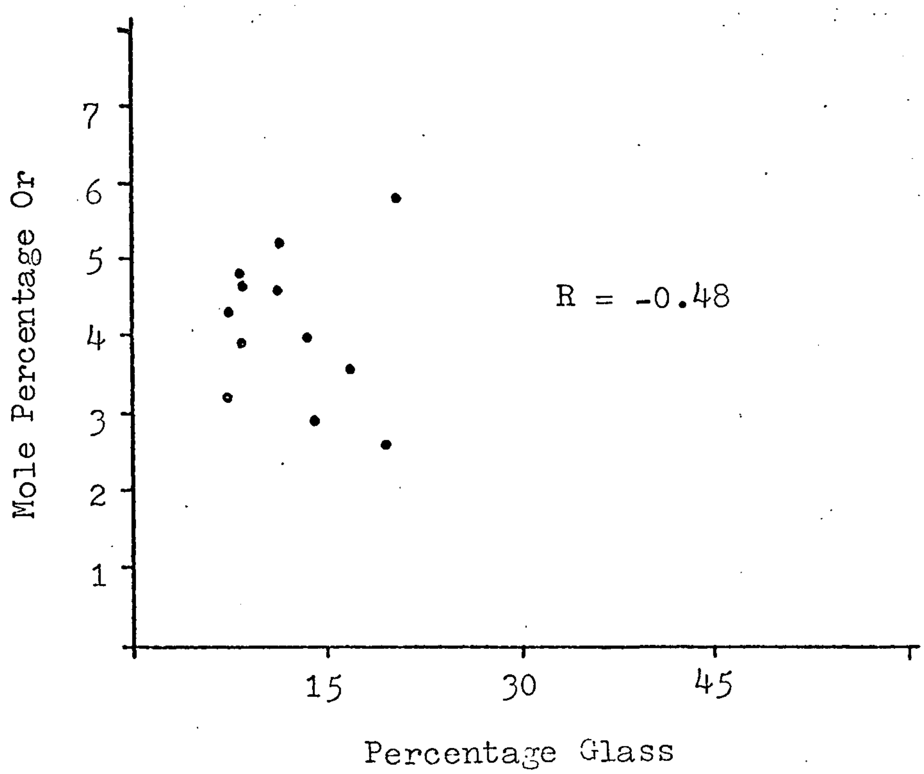

Fig. 9. Or content versus percentage glass

obtained by extrapolation from I.I. = 0 curve). The I.I. values reported in this study fall within the range of values as reported for tholeiite basalt (Hoffer, 1968). The average I.I. of groundmass plagioclases is approximately 23.

Structural State Versus Composition

A low negative correlation (linear) was found to exist between the structural state, expressed as I.I. unit, and the An content of the groundmass plagioclase ($R = -0.33$) (Fig. 10). In addition, a moderate positive correlation (linear) was found between Or content and structural state units ($R = 0.65$) (Fig. 11). As the structural state becomes higher (more disordered), the An content of the groundmass plagioclase increases and the Or content decreases.

Structural State Versus Percentage of Associated Glass

A low negative correlation (linear) was found between structural state of the groundmass plagioclase and the proportion of associated glass, as shown in Fig. 12. In samples that contain a small percentage of glass, the groundmass plagioclase have an intermediate order whereas samples with large amounts of glass contain groundmass plagioclase of higher structural state (less order).

Structural State Versus Size of Groundmass Plagioclase

The structural state and size of the groundmass plagioclase show a marked positive correlation (linear) (Fig. 13). This indicates as the size of the groundmass plagioclase decreases the amount of disorder decreases; the largest crystals are the most ordered.

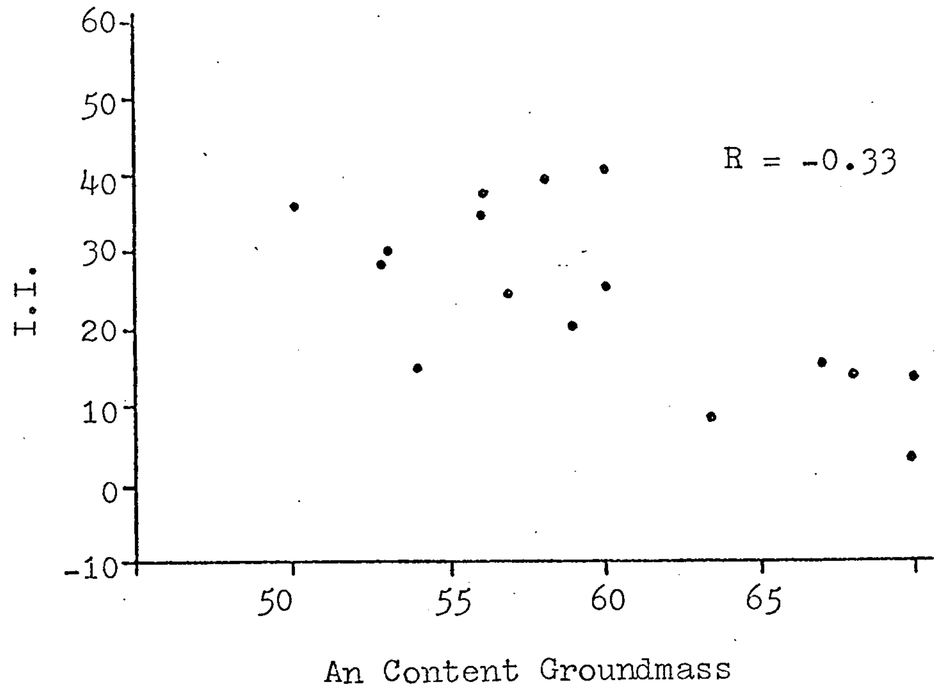

Fig. 10. Intermediacy Index (I.I.) versus An content of groundmass plagioclase

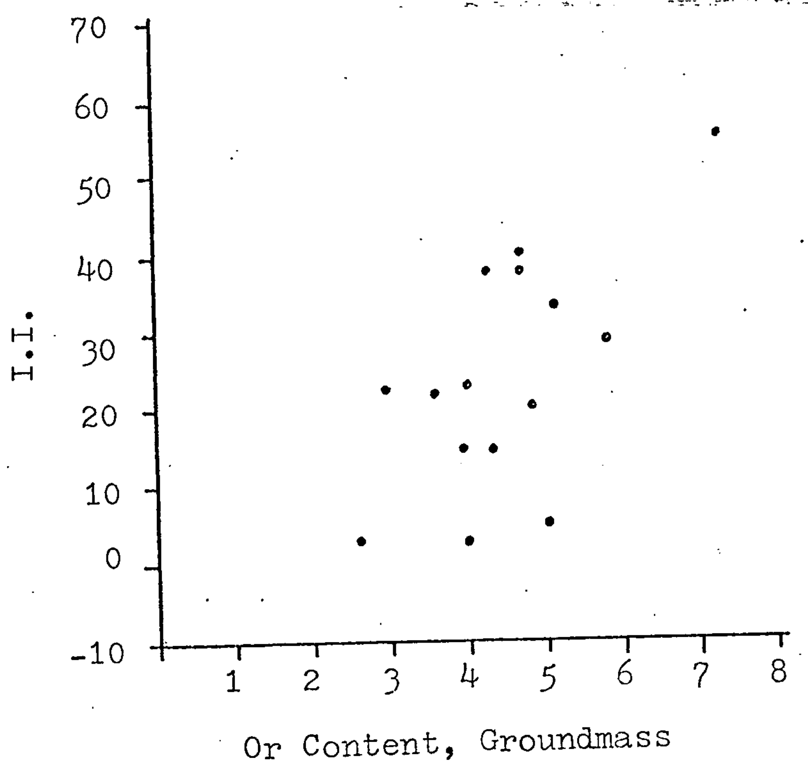

Fig. 11. Intermediacy Index (I.I.) versus Or content of groundmass plagioclase

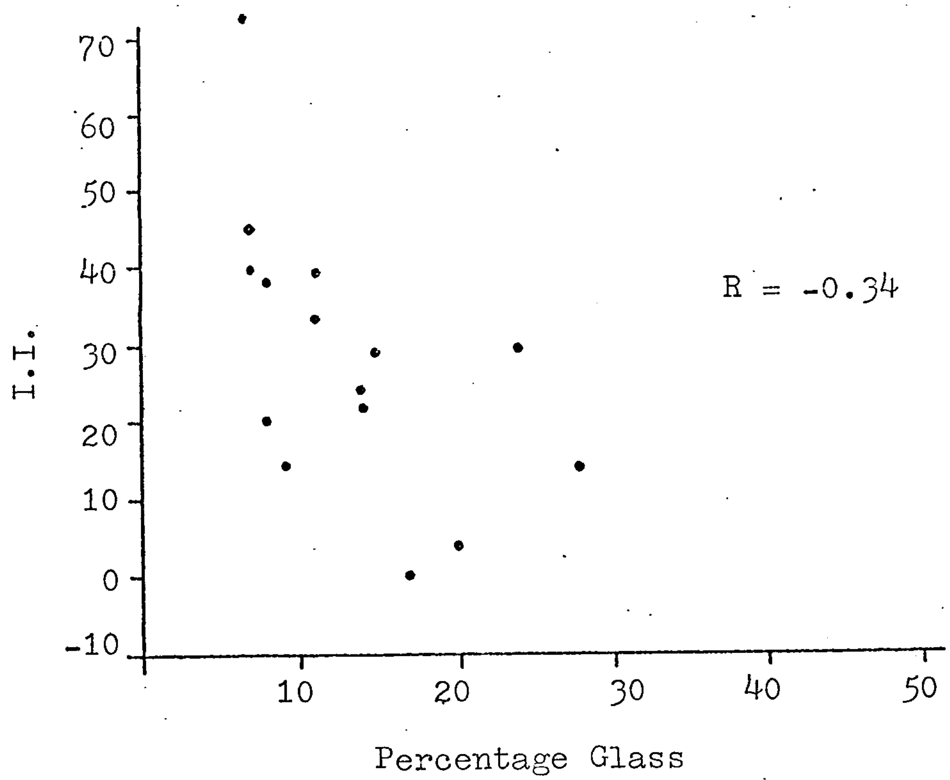

Fig. 12. Intermediacy Index (I.I.) versus percentage of glass

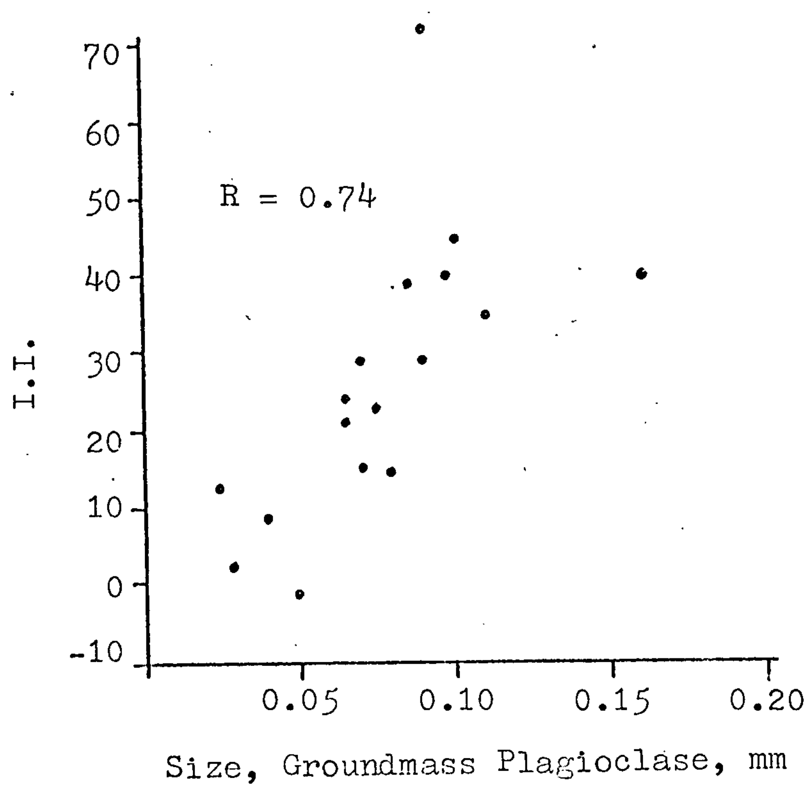

Fig. 13. Intermediacy Index (I.I.) versus size of groundmass plagioclase

Structural State of Phenocryst Plagioclase

The structural state of the phenocryst plagioclase varies from high to low order. Expressed as the intermediacy index, I.I., values range from 0 to 114. The average I.I. value of the phenocrysts is approximately 53.

The only significant correlation found with the phenocrysts is between degree of order and Or content ($R = 0.75$) (Fig. 14). This shows that samples possessing highest Or content are those of highest degree of order.

Relationship of Structural State of Phenocryst and Groundmass Plagioclase

As a group, phenocryst plagioclases possess more order than the groundmass plagioclases. The average I.I. value of the phenocrysts is 53 compared to 23 for the groundmass plagioclase (see Figs. 11 and 12).

Summary

In summary, the following conclusions can be stated concerning the variation of the structural state of the phenocryst and groundmass plagioclase:

1. The structural state of the groundmass plagioclase is related inversely to An content (low degree), directly to Or content (marked degree), directly to size (marked degree), and inversely to the proportion of associated glass (low degree).
2. The structural state of the phenocryst plagioclase varies directly with Or content (marked degree).
3. The groundmass plagioclases are generally more disordered than the phenocryst plagioclases.

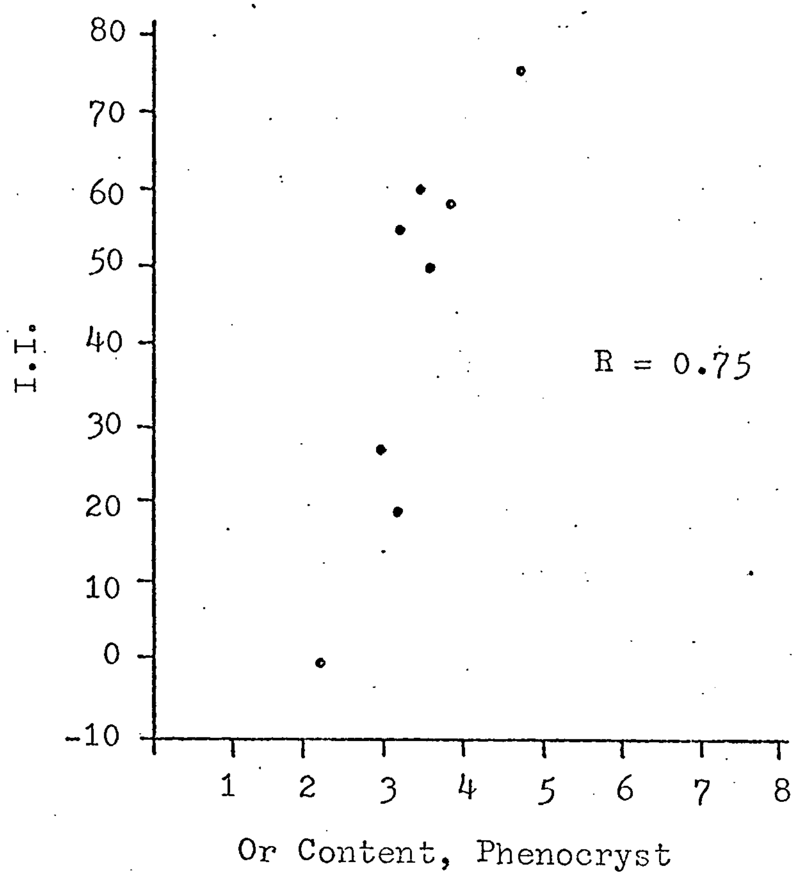

Fig. 14. Intermediacy Index (I.I.) versus Or content of phenocryst plagioclase

INTERPRETATION OF LABORATORY RESULTS

Relationships Investigated

The relationships of the chemical composition, size and structural state of plagioclase, and the proportion of associated glass from samples of the Potrillo Basalt are not random. It appears that these variations reflect the crystallization history of the lavas. For the sake of clarity, this section is divided into four parts in which the textural variations (size of the groundmass plagioclase crystals and the proportion of glass) and compositional and structural state variations of the plagioclase are discussed in terms of their origin, significance, and relationship to the crystallization history of the basalt. The fourth part of this section is devoted to the plagioclase mineralogy of lunar basalt and the significance of this study to the petrology of lunar basalts.

Textural Variations

The factors that determine the texture of any igneous rock include the rate of cooling, bulk chemical composition, composition with regard to hyperfusibles, and pressure (Wahlstrom, 1950). The bulk composition of the samples from the Potrillo Basalt members is probably uniform. The similarity in the average composition of the plagioclase phenocrysts from samples of each member suggests that these first-formed crystals of plagioclase represent crystallization from the same melt under similar conditions. Although compositional variations exist in the groundmass plagioclase, and the proportions of plagioclase, pyroxene, and glass vary from sample to sample, there is no evidence that the bulk chemical composition changed during crystallization.

The content of the hyperfusibles and the effect of pressure during crystallization are hard to appraise, but it seems likely that the influence of pressure was small because of the crystallization at the surface. Because of the release of pressure during extrusion of the magma the influence of concentrated mineralizers probably was small, except perhaps locally.

Therefore, if it is assumed that the bulk composition, content of hyperfusibles, and pressure were approximately the same for all the samples after extrusion, then the rate of cooling was the primary factor in determining the final texture. However, in small areas volatile constitutents and pressure may have influenced the cooling history of the lava and, therefore, the final texture.

The relationship of the size (width) of the groundmass plagioclase and the proportion of associated glass indicates that there were variations in the rate of cooling after extrusion of the magma. In samples in which the proportion of glass is small, representing conditions of relatively slow cooling, the average size of the groundmass plagioclase crystals is relatively large. Conversely, small groundmass plagioclase crystals are found in samples with a large amount of glass, and formed under conditions of rapid cooling. The negative correlations between the average size of the groundmass plagioclase crystals and the proportion of associated glass are marked ($R = -0.72$ to $R = -0.87$) (see Figs. 2 and 3).

In summary, it can be stated that the plagioclase phenocrysts crystallized at depth under conditions of slow cooling, before the crystallization of the groundmass. The groundmass plagioclase crystallized during or after extrusion of the magma under conditions of more rapid and variable cooling.

Compositional Variations

In the last section it was shown that Potrillo samples containing groundmass plagioclase of high An content characteristically possess small groundmass plagioclase crystals set in a large proportion of glass. Conversely, small amounts of glass are associated with large plagioclase groundmass crystals of low An content. This indicates that samples representing rapid cooling possess groundmass plagioclase of highest An content and lowest Or content whereas those that cooled more slowly contain groundmass plagioclase of low An content and higher Or content. The rate of cooling is related, therefore, not only to the size of the groundmass plagioclase crystals and the amount of glass, but also to the composition of the groundmass plagioclases. With regard to the plagioclase phenocrysts, no significant relationship was found to exist between the composition and the rate of cooling, as indicated by the proportion of glass.

The variation of An content of the groundmass plagioclase is due primarily to variation in the rate of cooling under conditions of fractional crystallization (Hoffer, 1966). The first formal crystals (phenocrysts) have the highest An contents. Under conditions closely approaching equilibrium many of the early-formed crystals reacted with the melt and were converted to more sodic forms. After (or during) extrusion of the magma the rate of cooling influences the composition of the groundmass plagioclase. This is suggested because of the correlations that exist between An content and size of the proportion of associated glass. In addition, those groundmass plagioclases crystallizing under conditions of slow cooling would be expected to contain the highest Or contents because of alkali enrichment in the magma and this is the case.

Structural State Variations

The results of structural state determinations indicate that the degree of order of groundmass plagioclase is related to size, An content, Or content and amount of associated glass. The degree of orderness of phenocryst plagioclase is a function of Or content. The structural state of the phenocryst plagioclase is lower than that of the corresponding groundmass crystals (I.I. 53 versus 23, respectively).

The degree of orderness of both the phenocryst and groundmass plagioclase can be explained in terms of rate of cooling. As the magma cooled at depth plagioclase phenocrysts crystallized which were primarily in the state of maximum disorder. As cooling proceeded, after extrusion, accompanied by the crystallization of the groundmass plagioclase, the structural state of the earlier phenocrysts tended to change toward a more ordered state. The phenocrysts would therefore have had more cooling time and therefore possess more order than groundmass crystals. In addition, it has been found that the amount of Or content influences phenocrysts order. Those phenocrysts plagioclases of greatest Or content are the most ordered. However, examination of Figs. 11 and 14, will show that Or content more strongly influences the degree of order in phenocryst compared to groundmass plagioclase.

The degree of order of the groundmass plagioclase is also influenced by rate of cooling and Or content. Those of highest An content (smallest size and associated with the most glass — indicating most rapid cooling) possess the most disorder and are of lowest Or content. In contrast, plagioclase of lowest An content (largest size and associated with the least amount of glass — indicating slow cooling) possess the most ordered state; these crystals also contain higher Or contents. Baumbauer et al., (1967) have indicated that Or content of plagioclase has a noticeable effect on the degree of orderness; high Or content will tend to produce more order.

In a study of the structural state of phenocryst and groundmass plagioclase from a tholeiite basalt it was found in samples containing groundmass plagioclase more calcic than An_{50} the phenocrysts were more disordered than the associated groundmass plagioclase (Hoffer, 1968). The results reported here for phenocrysts in alkali basalt is the opposite. Perhaps, the alkali basalt phenocrysts contain more Or molecule and are therefore more ordered. Unfortunately, the Or content of the tholeiite plagioclase phenocrysts in the above study is not known.

Lunar Basalts

Lunar basalts consist of very fine-grained vesicular intersertal basalts (type "A" rocks) to medium-grained equigranular Ophitic basalts ("type B" rocks) (Hyndman, 1972). The lunar rocks typically contain more Fe and Ti, much less Na, and less K, Si, and Al compared to earth basalts (see Table 5).

Lunar basaltic plagioclases display high An content, commonly An_{73} to An_{91}, and a high to low degree of order (Smith et al., 1970 and Stewart et al., 1970) (see Table 6). Plagioclase from type A rocks — fine-grained, on the basis of calculated 2θ (131)-(1$\bar{3}$1), are completely ordered; the I.I. of the plagioclases is greater than 100 (Table 6). Type B plagioclase from medium-grained crystalline rocks are highly disordered with I.I. values averaging less than 0. The degree of disorder increases as the An content increases, the same as earth basaltic plagioclase. In contrast, lunar plagioclase of largest size are the most disordered. This may be due to differences in Or content; Smith et al., (1970) reports 0.23 and 0.34 percent K_2O in a large and small plagioclase crystal, respectively. If the larger crystals reported by Stewart et al., (1970) contain less K_2O than the small plagioclase crystals this might explain why the latter are more ordered. At present not enough data concerning size, structural state, and Or percent of lunar plagioclase are available to this author to state any conclusions.

Conclusions

The following conclusions can be made concerning plagioclase in alkaline olivine basalt:

1. Chemical variations, An and Or content, correlate with size and amount of associated glass, indicating that these variations are due, at least in part, to rate of cooling.

	Lunar Basalt Type A	Lunar Basalt Type B	Earth Basalt Alkali Basalt
SiO_2	40.23	40.57	47.1
TO_2	11.85	10.53	2.7
Al_2O_3	8.70	10.48	15.3
Fe_2O_3	0.00	0.008	4.3
FeO	19.44	18.56	8.3
MnP	0.28	0.27	0.17
MgO	7.76	7.07	7.0
CaO	10.49	11.63	9.0
Na_2O	0.61	0.58	3.4
K_2O	0.30	0.07	1.2
Cr_2O_3	0.35	0.30	–
P_2O_5	0.16	0.06	0.41

TABLE 5

Average chemical composition of Lunar and Earth basalts (from Hyndman, 1972).

Rock Type	B	B	B	A	A	A	A	A
Estimated Chemical Composition	85	83	81	78	75	75	74	73
Calculated °2θ (131)-(1$\bar{3}$1)	2.22	2.20	2.18	2.09	2.00	2.01	1.92	1.97
Intermediacy Index	<0	<0	0	98	>100	>100	>100	>100

TABLE 6

Composition and structural state of lunar plagioclase (from Stewart et al., 1970).

2. The degree of disorder of the plagioclase is determined by rate of cooling and composition, An and Or contents.
3. The Or content more strongly influences the degree of order in phenocryst versus groundmass plagioclase. Variations in Or content may explain the anomolous structural states of Type A lunar plagioclase.

APPENDIX I

Mineralogical Data of Plagioclase

Sample	Size of Grdm	Glass	2θ (131)-(1$\bar{3}$1)	I.I.	2θ (131)-(20)	I.I.	An	Or
26-eP	0.05	19	1.99	65	1.06	45	67	3.8
26-dP	0.06	9	2.00	63	1.09	55	67	3.4
26-cP	0.06	10	1.95	105	1.07	53	68	4.7
26-bP	0.06	12	1.96	130	1.10	95	71	3.6
26-aP	0.09	7	1.99	60	1.08	53	66	3.1
13-Ig	0.11	11	1.92	45	1.11	25	56	5.1
13-Hg	0.07	14	1.97	40	1.05	8	60	4.0
13-GP	0.01	43	1.87	90	1.12	44	60	3.6
13-Fg	0.02	41	1.97	43	1.03	1	60	3.1
13-Eg	0.07	15	1.95	13	1.11	17	53	-
13-Cg	0.07	11	1.93	50	1.11	32	58	4.3
13-Bg	0.09	24	1.89	40	1.13	22	55	5.8
13-Ag	0.16	8	1.94	36	1.13	34	56	4.7
2Ag	0.08	7	1.94	25	1.13	5	54	4.3
2BP	0.07	10	2.06	10	1.00	-10	63	2.2
41	0.04	18	2.09	20	0.96	-3	70	-
40	0.07	8	2.06	25	1.00	5	67	3.9
39	0.10	7	2.01	60	1.04	30	67	3.2
38g	0.65	8	2.01	23	1.07	18	60	4.8
38P	0.65	8	1.98	68	1.13	80	66	-
36Bg	0.03	19	2.12	14	0.99	-7	69	2.6
35AP	0.70	9	2.10	30	0.96	30	73	-
32g	0.66	14	2.01	24	1.09	26	60	2.9
32P	0.66	14	2.03	47	1.05	40	67	-
2q	0.03	28	2.08	18	1.00	10	68	-
25ag	0.06	13	2.06	-30	1.10	5	50	-
KHZ	-	0	1.98	4	1.08	-3	53	4.0
A-23	0.05	17	2.07	8	1.01	-10	62	-
A-19	0.06	17	2.05	30	1.03	14	66	3.6

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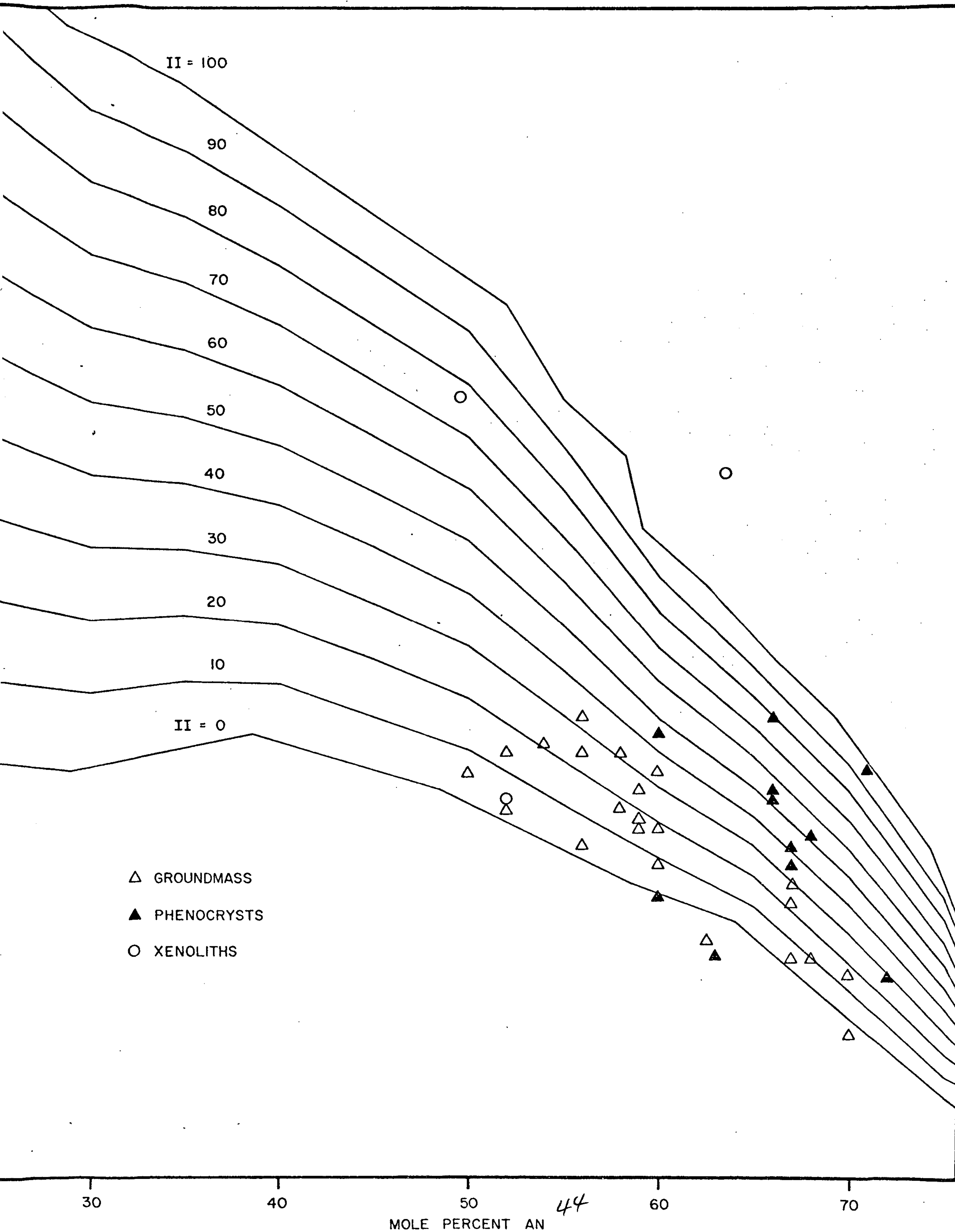
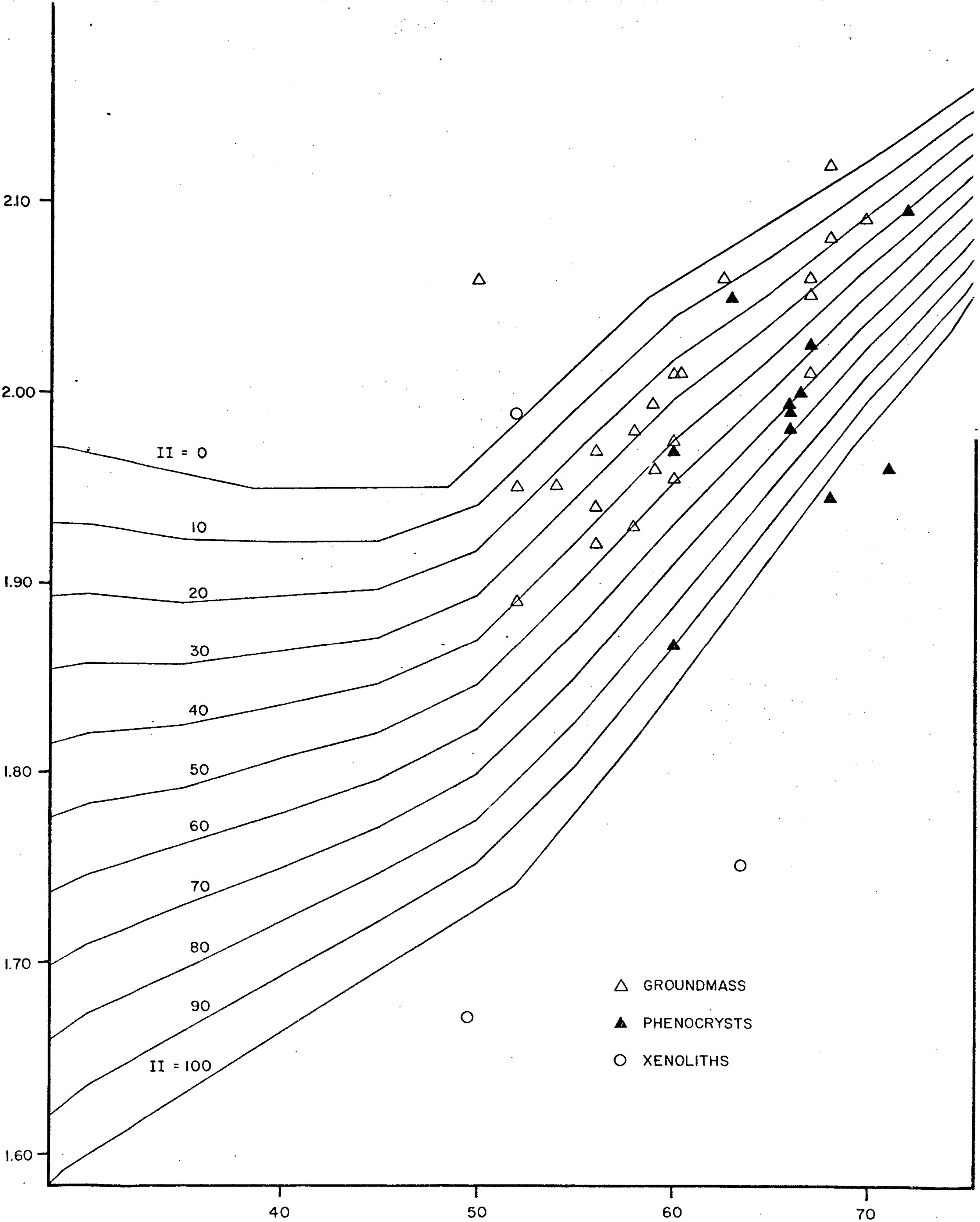


II = 100
90
80
70
60
50
40
30
20
10
II = 0
GROUNDMASS
PHENOCRYSTS
XENOLITHS
30
40
50
60
70
MOLE PERCENT AN

44

PLATE 2



2.10
2.00
1.90
1.80
1.70
1.60
II = 0
10
20
30
40
50
60
70
80
90
II = 100
GROUNDMASS
PHENOCRYSTS
XENOLITHS
40
50
60
70
MOLE PERCENT AN

45

PLATE 3